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Classification and dynamic calibration of ionization sensors and detectors†

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Abstract. The dynamic characteristics of the detection process are defined and analysed. Through-flow and nonthrough-flow modes of operation are defined as reference points in a continuous range of possible modes of operation. A linear detector is defined as a detector whose instantaneous output is a linear combination of outputs due to beam flux and beam density. The dynamic calibration function of the detector relates the time-dependent detector signal to the time-dependent molecular-beam conditions at the detector entrance. A procedure for determining the dynamic calibration function of a wide class of linear ionization detectors from time-of-flight measurements in a modulated beam of known speed distribution, density and modulator gate function is presented. The moments of the dynamic calibration function are obtained from moments of the measured time-of-flight signal, of the speed-distribution function and of the modulator gate function.

As an application of the procedure, the three lower moments of the dynamic calibration function have been obtained for a new type of molecular-beam detector by calibration in a modulated thermal molecular beam of known density. A physically meaningful analytical expression for the dynamic calibration function is derived from these moments.

1. Introduction

Ionization-type devices are used as sensing elements for measuring pressure (pressure gauges), composition (mass spectrometers) and speed distributions (molecular-beam detectors). Such sensors are calibrated frequently by measuring the ion current as a function of the density of a gas either at equilibrium or under steady-state flow conditions. The use of calibration constants obtained under such conditions can yield serious misinterpretations of measurements at unsteady-state flow conditions (e.g., measurements from satellites under unsteady conditions). The classification, analysis and calibration described here are the results of an effort to eliminate such misinterpretations.

2. Classification and analysis

Consider a pulse of electrically neutral and chemically stable molecules admitted into a detector. This pulse can be characterized by the time-dependent values of the instantaneous rate $N_t(t)$ at which molecules cross the detection plane and the instantaneous number $N_x(t)$ of molecules per unit path length at this plane. A fraction c of the admitted molecules pass through the ionizing region unimpeded except for collisions with electrons. The remaining fraction $(1-c)$ collide with the walls of the detector to produce an excess molecule density within the cavity (relative to the combined beam and background densities) which is eventually depleted by net effusion to the steady-state environment outside the detector. Modes of operation realized when c equals 1 and 0 (reference points in a continuous range of possible modes of operation) are called the 'through-flow' mode and the 'nonthrough-flow' mode.

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A 'linear detector' is defined as a detector whose instantaneous output is a linear combination of outputs due to beam flux and bean density. More specifically,

$$I^+(t)=(1-c)\,I_{\mathrm{ntf}}{}^+(t)+cI_{\mathrm{tf}}{}^+(t), \tag{1}$$

where $I^+(t)$ is the detector signal and the subscripts ntf and tf refer respectively to nonthrough-flow and through-flow operation. A similar linear expression relates the jth (non-normalized) moments of the three detector signals appearing here.

If the characteristic time τ for effusion from the detector and for signal processing is independent of time t, then the detector signal due to nonthrough-flow operation is related to $N_{\mathrm{t}}(t)$ by

$$I_{\mathrm{ntf}}{}^+(t)=K_1\int_0^t \exp\,(-\lambda/\tau)\,N_{\mathrm{t}}(t-\lambda)\,d\lambda, \tag{2}$$

where K_1 is a calibration constant. Moment relations of particular interest include

$$\mu_0\{I_{\mathrm{ntf}}{}^+(t)\}=K_1\tau\mu_0\{N_{\mathrm{t}}(t)\} \tag{3}$$

$$\eta_1\{I_{\mathrm{ntf}}{}^+(t)\}=\tau+\eta_1\{N_{\mathrm{t}}(t)\} \tag{4}$$

$$\nu_2\{I_{\mathrm{ntf}}{}^+(t)\}=\tau^2+\nu_2\{N_{\mathrm{t}}(t)\} \tag{5}$$

where $\mu_0\{\ \}$, $\eta_1\{\ \}$ and $\nu_2\{\ \}$ are respectively the zeroth (non-normalized) moment, the first (normalized) moment and the second (normalized) central moment (the variance).

If the characteristic time for effusion and for signal processing is sufficiently small, then the detector signal due to through-flow operation is related to $N_{\mathrm{x}}(t)$ by

$$I_{\mathrm{tf}}{}^+(t)=K_2N_{\mathrm{x}}(t), \tag{6}$$

where K_2 is a calibration constant. Moment relations of particular interest include

$$\mu_0\{I_{\mathrm{tf}}{}^+(t)\}=K_2\mu_0\{N_{\mathrm{x}}(t)\} \tag{7}$$

$$\eta_1\{I_{\mathrm{tf}}{}^+(t)\}=\eta_1\{N_{\mathrm{x}}(t)\} \tag{8}$$

$$\nu_2\{I_{\mathrm{tf}}{}^+(t)\}=\nu_2\{N_{\mathrm{x}}(t)\}. \tag{9}$$

The number of moments considered during calibration depends upon the amount of information (e.g., density and speed-distribution parameters) which is to be extracted in the application of the detector.

Obvious simplifications are realized if the detector operates either as a nonthrough-flow detector ($c=0$) or as a through-flow detector ($c=1$). The hypothesis that a given detector is a nonthrough-flow detector may be tested by comparing the values of τ obtained from equations (4) and (5). Similarly, the hypothesis that it is a through-flow detector may be tested by comparing the left-hand and right-hand sides of equation (8).

Effects of non-linearity can be minimized by either (a) operating the detector in the through-flow mode, or (b) ensuring that those molecules which collide with detector walls are accommodated thermally to the detector before leaving the detector. The nonthrough-flow operation of the detector is essentially linear if the change in τ due to a change in energy level of the admitted molecules is small in comparison with $\eta_1\{N_{\mathrm{t}}(t)\}$.

3. Typical dynamic-calibration results

A new type of molecular-beam detector (called an Orbitron detector after the pressure gauge which is designed on the same principle (Mourad *et al.* 1964)) was developed to provide the sensitivity required to measure the flux distribution of scattered products of collisions of modulated molecular beams with solid surfaces (Alcalay 1967, Alcalay and Knuth 1968a). Relatively large electron-path lengths are realized by orbiting the ionizing electrons in an electrostatic field between two concentric cylinders. (The resulting relatively low electron currents would be particularly advantageous for measurements from satellites and space vehicles, where electrical power is costly.) The dynamic calibration of this detector is summarized here; for its design, see Alcalay (1967).

The dynamic response of this detector to a modulated thermal molecular beam of known density was recorded for several angular speeds of the chopper and for several source densities. Zeroth, first and second-central moments of the recorded signal were measured by a suitable planimeter. A nonthrough-flow linear detector was hypothesized with the understanding that this hypothesis would be tested using equations (4) and (5). The moments of $N_x(t)$ appearing in equations (3)–(5) can be related (Alcalay 1967, Alcalay and Knuth 1968b) to moments of the speed-distribution function $f(s)$ and the modulator gate function $A(t)$ by

$$\mu_0\{N_t(t)\}=\gamma n_b \mu_0\{\phi(t)\}\ \mu_0\{A(t)\} \tag{10}$$

$$\eta_1\{N_t(t)\}=\eta_1\{\phi(t)\}+\eta_1\{A(t)\} \tag{11}$$

$$\nu_2\{N_t(t)\}=\nu_2\{\phi(t)\}+\nu_2\{A(t)\}, \tag{12}$$

where γ is the most probable random speed, n_b is the number density of beam molecules, $\phi(t)\equiv sf(s)\,L/\gamma t^2$ is the time-domain analog of the flux-distribution function $sf(s)$, $s\equiv u/\gamma$ is the speed ratio, u is the molecular speed, L is the distance from the chopper to the detector and t is the time required for a molecule with speed u to traverse a distance L. The modulator gate function was approximated by a trapezoid, for which (Alcalay 1967, Alcalay and Knuth 1968b)

$$\mu_0\{A(t)\}=A_b\alpha/\omega \tag{13}$$

$$\eta_1\{A(t)\}=(\alpha+\psi)/2\omega \tag{14}$$

$$\nu_2\{A(t)\}=(\alpha^2+\psi^2)12\omega^2, \tag{15}$$

where A_b is the beam cross-sectional area, α is the chopper slit aperture angle, ψ is the angle through which the rotor must turn in order to sweep a radial line on the rotor disk across the beam and ω is the angular speed of the rotor. The equations obtained by eliminating the moments of $N_t(t)$ and $A(t)$ from equations (3)–(5) and (10)–(15) motivate the choice of coordinates used in figures 1–4 and, consequently, the fitting of straight lines to the plotted data. For a thermal molecular beam (oven beam), the moments of $\phi(t)$ can be related (Alcalay 1967, Alcalay and Knuth 1968b) to L/γ by

$$\mu_0\{\phi(t)\}=2/\sqrt{\pi} \tag{16}$$

$$\eta_1\{\phi(t)\}=(\sqrt{\pi}/2)\,(L/\gamma) \tag{17}$$

$$\nu_2\{\phi(t)\}=(1-\pi/4)\,(L/\gamma)^2. \tag{18}$$

One finds, from equations (3), (10), (13) and (16) and the slopes of the straight lines in figures 1 and 4, that $K_1\tau=3{\cdot}10\times10^{-22}$ C molecule^{-1} and $3{\cdot}35\times10^{-22}$ C molecule^{-1} respectively; from equations (4), (11), (14) and (17) and the intercept of the straight line of figure 2, that $\tau=3{\cdot}1\times10^{-4}$ s; and from equations (5), (12), (15) and (18) and the intercept of the straight line of figure 3, that $\tau^2=1{\cdot}02\times10^{-7}$ s^2. The good agreement of the values of $K_1\tau$ obtained from figures 1 and 4 indicates that the zeroth moment of the dynamic function of the detector and its electronics may be obtained from calibration data for either several chopper angular frequencies or several beam-source densities, whichever is more convenient. The good agreement of the values of τ obtained from figures 2 and 3 justifies the hypothesis of a linear nonthrough-flow detector. (A procedure for evaluating τ directly from a signal obtained in an application is demonstrated by Alcalay and Knuth 1968b.)

Since (a) the ionization volume V is about 20 cm^3, (b) the emission current I^- is $2{\cdot}7\times10^{-3}$ A and (c) the ionization cross section σ for argon is about $2{\cdot}3\times10^{-16}$ cm^2 atom^{-1}, the mean electron-path length ($=K_1V/\sigma I^-$) is about 33 cm, which is more than an order of magnitude greater than the detector diameter.

The through-flow sensitivity ($=K_1V$) is about $2{\cdot}0\times10^{-17}$ A (atom cm^{-3})$^{-1}$. This sensitivity reflects the relatively large mean electron-path length.

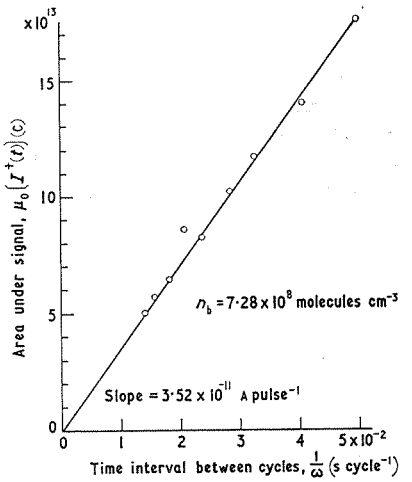

Figure 1. Integral of ion-current signal as a function of inverse chopper frequency.

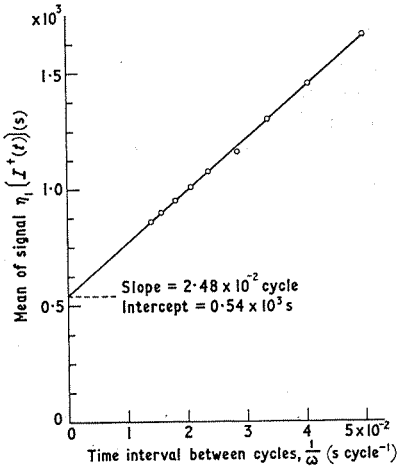

Figure 2. Mean of ion-current signal as a function of inverse chopper frequency.

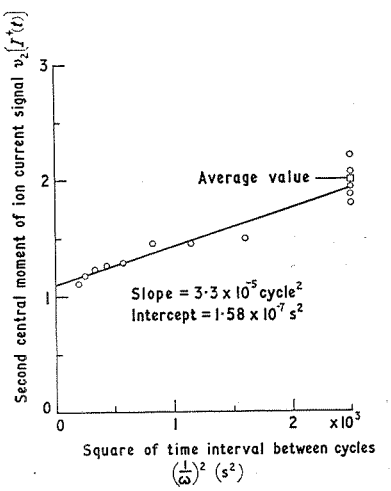

Figure 3. Second central moment of ion-current signal as a function of square of inverse chopper frequency.

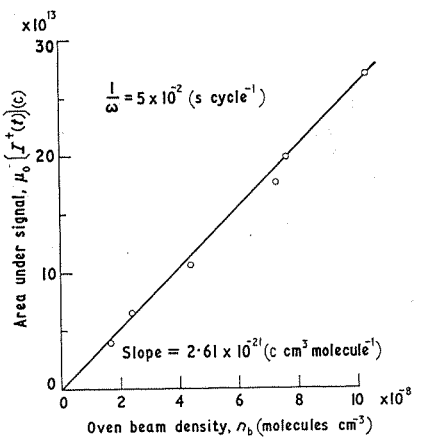

Figure 4. Integral of ion-current signal as a function of beam density.

4. Closure

The present dynamic-calibration method is expected to be valuable in designing and calibrating ionization sensors useful in measurements of the density and composition of the upper atmosphere by means of orbiting satellites. In addition, the authors hope that the methods and concepts reported here will be useful in characterizing the performance of ion-vacuum pumps.

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